Pulse-Shape Analysis of PDM-QPSK Modulation Formats for 100 and 200 Gb/s DWDM transmissions

Andrés Macho Ortiz · Paloma R.Horche

Abstract Advanced optical modulation format polarization-division multiplexed quadrature phase shift keying (PDM-QPSK) has become a key ingredient in the design of 100 and 200-Gb/s dense wavelength-division multiplexed (DWDM) networks. The performance of this format varies according to the shape of the pulses employed by the optical carrier: non-return to zero (NRZ), return to zero (RZ) or carrier-suppressed return to zero (CSRZ). In this paper we analyze the tolerance of PDM-QPSK to linear and nonlinear optical impairments: amplified spontaneous emission (ASE) noise, crosstalk, distortion by optical filtering, chromatic dispersion (CD), polarization mode dispersion (PMD) and fiber Kerr nonlinearities. RZ formats with a low duty cycle value reduce pulse-to-pulse interaction obtaining a higher tolerance to CD, PMD and intrachannel nonlinearities.

Keywords Modulation formats · Quadrature Phase Shift Keying · duty cycle · spectral efficiency (SE) · intrachannel nonlinearities

A.Macho · P.R.Horche (✉)
Departamento de Tecnología Fotónica y Bioingeniería
Escuela Técnica Superior de Ingenieros de Telecomunicación
Universidad Politécnica de Madrid, Avda. Complutense nº30
28040 Madrid, Spain

A.Macho
e-mail: macho.andres@tfo.upm.es
telephone: +34649994228

P.R.Horche
e-mail: phorche@tfo.upm.es
telephone: +34913367306
fax: +34913367319

1 Introduction

Nowadays, communication networks are required to provide an enormous data transport capacity to solve the continuous increase of internet traffic. The amount of traffic carried on backbone networks has been growing exponentially over the past two decades. The required network bandwidth increases between 40% and 60% per year due to the rapid emergence of new communication services: social networking, 4K video, data traffic of smartphones and tablets, and cloud services. The explosion of these services has led to the necessity of implementing new technologies in optical transport networks which increase their capacity [1,2,3].

Since the 90s, traffic demand in core optical networks has been covered by WDM systems, which have been able to scale up their capacity from 10-Mb/s per channel to 100-Gb/s at present [4]. Migration from 40 to 100-Gb/s has not been so immediate because it has required additional transmission techniques that would allow this bit rate compatibility with DWDM-50 GHz grid. Polarization-division multiplexing (PDM) was developed to increase spectral efficiency of QPSK modulation format from 2 b/s/Hz to 4 b/s/Hz. In addition, the use of coherent detection, digital signal processing (DSP) and forward error correction (FEC) techniques, the standard 100 Gigabit Ethernet (GbE) became a reality at the end of 2010 and at the beginning of 2011 [2]. With the impulse and development of Cloud Computing, the capacity offered by DWDM networks could be short in the next years, so optical communications should survey beyond 100-G, being the next step the standard 400 GbE, estimated for the year 2016 [3,5,6].

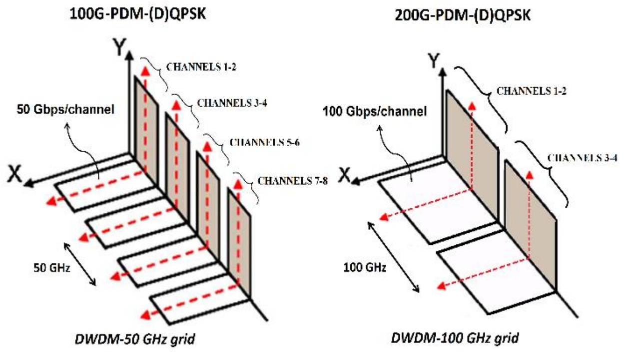

Fig. 1. PDM-(D)QPSK modulation formats for 100 and 200-Gb/s transmissions in DWDM systems.

As previous step to the 400 GbE, the immediate necessity is to migrate from 100-G to 200-G. To achieve this bit rate is likely to continue initially with the parallel transmissions approach: 5 parallel lanes of 40-Gb/s or 2 parallel lanes with quickly maturing 100-Gb/s technology, [3]. But the tendency is to integrate 200-Gb/s in 50 GHz grid through a single lane.

Therefore, high spectral-efficiency (S.E) PDM-M-QAM formats have been proposed to increase the S.E beyond 4 b/s/Hz. The main drawback of using dense digital constellations is their high vulnerability to the nonlinear effects of the optical fiber, increasing the system complexity to achieve long-haul transmissions with these formats [7]. The other disadvantage inherent to the use of dense digital constellations is that it would be necessary a higher resolution in the analogic-to-digital (ADC) converters of the coherent receiver [8].

Due to the difficulties to obtain long-haul optical transmissions with PDM-M-QAM formats [9], the International Telecommunication Union Standardization Sector (ITU-T) has enabled to leave the rigid grid of 50 GHz in 2012 with the proposal of flexible DWDM networks [10]. In this way, it is possible to avoid the use of PDM-M-QAM formats employing 200G-PDM-QPSK signals with 100 GHz between optical carriers (Fig. 1). For the integration in DWDM-50 GHz grid it is being studied the Nyquist filtering approach (N-WDM), which reduces the width of the main spectral lobe [11] at the expense of a strong filtering distortion. This penalty could be solved with Maximum-Likelihood Sequence Detection (MLSD) [12,13]. However, the abrupt transition band of Nyquist filtering is currently far from its implementation, so the practical approach is to use these formats over the grid of 100 GHz for 200-Gb/s transmissions.

The performance of PDM-(D)QPSK varies according to the line code that is employed over the pulses of the optical carrier. The question as to the 'best' optical

Modulation Formats 100/200-Gbps
PDM-NRZ-(D)QPSK
PDM-67%RZ-(D)QPSK
PDM-50%RZ-(D)QPSK
PDM-33%RZ-(D)QPSK
PDM-CSRZ-(D)QPSK

Table 1 Different pulse shapes in PDM-(D)QPSK modulation.

modulation format cannot be concluded until the pulse is fully shaped: NRZ, RZ or CSRZ (Table 1). Each of the options offers different tolerances to linear and nonlinear optical impairments:

- ASE noise
- Crosstalk and optical filtering distortion
- Chromatic dispersion
- PMD
- Fiber Kerr Nonlinearities

In this paper we will analyze the features of PDM-(D)QPSK in 100 and 200-Gb/s transmissions heeding the above physical impairments. The paper is organized as follows. Section II presents the architecture of the simulation scenario and its main parameters, in Section III is investigated the ASE noise tolerance, in Section IV is analyzed the crosstalk and optical filtering distortion, Section V is devoted to chromatic dispersion, Section VI measures the robustness of these formats to PMD, in Section VII the nonlinear regime is analyzed, and finally Section VIII concludes this paper.

2 Simulation scenario

The simulations have been performed with computational-aided design tool OptiSystem. The analysis of PDM-(D)QPSK depends largely each of the devices that make up the optical network, so that the results will be subject to the simulation scenario. For this reason the simulations of the next sections have been implemented over a generic model of DWDM network (Fig. 2) [14]. The system includes 16 wavelengths (32 optical channels due to PDM). For 100 and 200-Gb/s transmissions the spectral separation between super-channels is 50 and 100 GHz respectively. The frequency bands are 192.75 – 193.5 THz in the first case and 192.4 – 193.9 THz in the second case. Transmission is performed in 6x100-km spans with EDFA amplification. We have

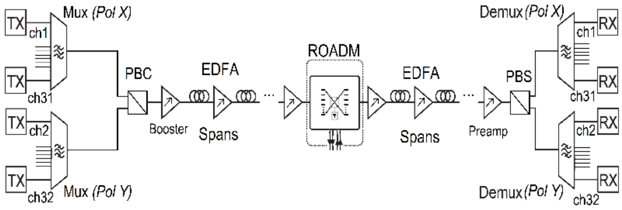

Fig. 2. Generic setup of a WDM system with polarization division multiplexing (PBC-Polarization Beam Combiner, PBS-Polarization Beam Splitter).

Parameter	**Value**
Laser linewidth (ECL)	100 KHz
MZM extinction ratio	30 dB
Noise Figure (EDFA)	5 dB
Dark Current (PIN)	10 nA
Responsivity (PIN)	0,9 A/W
Thermal noise	$1\text{x}10^{-22}$ W/Hz
Bandwidth in optical filters (Second-order Gaussian filters)	43 GHz (50 GHz grid) 85 GHz (100 GHz grid)
RF filters	Fourth-order Bessel filters
Cutoff frequency	0,75 x Rs
PRBS-Sequence length	32768 bits

Table 2 General parameters of the simulation scenario.

employed standard single-mode fiber (SSMF) or non-zero dispersion shifted fiber ($NZDSF^+$) depending on the simulation implemented on each section. The main fiber parameters are shown in Table 8. We have included in the optical link two multiplexers, two demultiplexers, a reconfigurable optical add-drop multiplexer (ROADM) and some optical filters to characterize the simulation scenario as realistically as possible. In each optical impairment discussed, the simulated scenario will have slight variations, but all of them share some general parameters (Table 2).

During the next sections the performance of PDM-(D)QPSK will be analyzed in the presence of the main physical impairments. The tolerance to ASE noise, crosstalk, optical filtering, chromatic dispersion, PMD and nonlinearities will be studied in order to discover the pulse-shape (NRZ, RZ or CSRZ) which provides the best performance in DWDM networks. QPSK and DQPSK have the same temporal and spectral profile, so the results of the analysis will be identical for both formats. We will refer to these two modulations under the joint notation of (D)QPSK. The only difference between them is that QPSK carries the information into the phase of optical pulses but DQPSK encodes the digital symbols into the phase transitions.

3 ASE noise tolerance

Essential mechanisms of power losses in an optical fiber are mainly derivatives of the absorption, spatial dispersion and power radiated to the cladding [15]. In long-haul transmissions, optical systems require optical amplification because fiber losses reduce the signal power below the detectability threshold of photodetectors. Optical amplifiers can be designed as lumped elements periodically spaced through the link forming several amplification spans typically spaced 80 to 100 km in terrestrial systems and 40 to 60 km in submarine transmissions [2,15]. Optical amplification can also be distributed by introducing gain along the transmission fiber.

The main drawback of optical amplifiers in a multispan scenario is the generation and accumulation of amplified spontaneous emission (ASE) noise in the optical spectrum. If multiple optical amplifiers are concatenated to periodically compensate for fiber loss, ASE builds up in the system, in analogy to the noise build-up in an electrical amplifier chain. This noise build-up is captured by the optical signal-to-noise ratio (OSNR), which degrades with every amplifier along the propagation path [16,17].

The ASE noise tolerance of 100 and 200-Gb/s PDM-(D)QPSK signals is fully characterized by the required OSNR ($OSNR_{req}$) [1], which is the OSNR that is needed to achieve a specified target BER. Excluding FEC overhead, the $OSNR_{req}$ for a $BER_{ref} = 10^{-12}$ was calculated in a single-channel back-to-back (B2B) scheme, where the transmitter is directly connected to the synchronous homodyne coherent receiver [18,19], without filters or optical fiber between TX and RX (Fig. 2). The goal is to discover the pulse-shape (NRZ, RZ or CSRZ) that offers better sensitivity. A higher sensitivity ensures greater tolerance to degradation by accumulation of ASE noise in the spectrum. Table 3 gives the results obtained in this

Modulation Format *Coherent Detection*	$\mathbf{OSNR_{req}}$ ($BER_{ref}=10^{-12}$) 100 Gb/s	$\mathbf{OSNR_{req}}$ ($BER_{ref}=10^{-12}$) 200 Gb/s
PDM-NRZ-(D)QPSK	21,0 dB	24,9 dB
PDM-67%RZ-(D)QPSK	20,3 dB	24,2 dB
PDM-50%RZ-(D)QPSK	20,2 dB	24,1 dB
PDM-33%RZ-(D)QPSK	**19,8 dB**	**23,7 dB**
PDM-CSRZ-(D)QPSK	20,2 dB	24,1 dB

Table 3 Sensitivity of PDM-(D)QPSK signals (0.1-nm resolution bandwidth).

section. These values may differ from other works cited in the bibliography due to various optical and electronic hardware implementation aspects, including drive waveforms, filter characteristics and modulator extinction ratio [4,16,20]. Nevertheless, there are some general facts which are worth mentioning.

QPSK and DQPSK, which are multilevel modulations, require only 0.5-dB more OSNR than PSK and DPSK signals in coherent and differential interferometric detection [20,21]. Leaving aside TX/RX complexity aspects, the good OSNR performance makes PDM-(D)QPSK an attractive candidate for optically routed networks that require a trade-off between sensitivity and spectral efficiency. OSNR values listed in Table 3 haven been measured in both polarizations and in a 12.5-GHz optical reference bandwidth.

RZ pulses require ~1 dB less OSNR for identical BER than NRZ. Particularly, signals with a low duty cycle require less OSNR to obtain the specified target BER. The shorter the pulse width, the higher the sensitivity of PDM-(D)QPSK. We can see in Table 3 that a reduction in the duty cycle decreases $OSNR_{req}$ in the modulation format. Consequently, PDM-33%RZ-(D)QPSK ends emerging as the option that offers the best sensitivity. In contrast, NRZ version has the lowest sensitivity with 21-dB and 25-dB in 100 and 200-Gb/s transmissions, respectively.

On the other hand, with PDM-CSRZ-(D)QPSK we can achieve a sensitivity similar to PDM-50%RZ-(D)QPSK with a higher duty cycle (67%). This is mostly due to the reduced impact of ISI over the CSRZ pulses.

4 Crosstalk, optical filtering and spectral efficiency

Some formats are better suited than others when it comes to tight WDM channel packing, quantified by its spectral efficiency. Apart from important SE-dependent nonlinearity considerations, in DWDM networks with high spectral efficiency there are two concern impairments arising from dense WDM channel spacing: crosstalk and filter narrowing.

An optical channel can be affected by two different types of crosstalk [19]: linear or interchannel crosstalk (undesirable power of adjacent DWDM channels in the desired band generating interferences at square-law detection) and homodyne or intrachannel crosstalk (also known as Multipath Interference or MPI [20], which describes the coherent interference of a signal with residual signals at the same wavelength due to imperfect, reflective fiber connectors, double-Rayleigh backscattering, or due to from imperfect drop capabilities of OADMs…). The former is quite easy to avoid with optimal filtering of the desired band, but the latter is hardly removed by optical filters.

In general, phase modulated signals are more tolerant to linear and homodyne crosstalk than intensity modulations [21,22]. In analogy to linear crosstalk, undesirable power in-band with the signal gives rise to signal-MPI beat noise at square-law detection becoming amplitude jitter in the eye diagram, so that the eye penalty in PDM-(D)QPSK is lower than in OOK signals due to the information is encoded in the optical phase. Strictly, the impact of crosstalk on system performance depends on the number of interferers, the OSNR delivered, the modulation format and the signals waveform (in particular the signal extinction ratio, and the phase coherence of the interfering signals).

The tolerance of PDM-(D)QPSK to linear and homodyne crosstalk has been analyzed. We have compared different pulse shapes affected by the same crosstalk ratio and we do not find major differences between them. The narrowband PDM-NRZ-(D)QPSK signal is less susceptible to generate linear crosstalk penalties. Meanwhile, a broadband modulation spectrum is less susceptible to MPI penalties due to reduced signal-MPI beat noise (RZ formats) [20].

On the other hand, in order to narrow the bandwidth of 100 and 200-Gb/s PDM-(D)QPSK signals, it is necessary to filter them with the optimal bandpass to avoid crosstalk impairments. However, the main problem of optical filtering appears in DWDM networks with high spectral efficiency, where the concatenation of multiple ROADM’s narrows the overall optical filter bandwidth and distorts the signals. In this situation, it is particularly relevant to analyze the tolerance of PDM-(D)QPSK to filtering distortion.

In order to simulate realistic conditions, the set of network devices with filters in their architectures (mux, demux, ROADM's ...) is modeled as an equivalent cascade of filters between TX and RX in a B2B scenario. We have analyzed two different cases:

a) *100-Gb/s in DWDM 50-GHz grid*: five second-order Gaussian bandpass filters with Full-Width at Half-Maximum (FWHM) bandwidth of 43 GHz.
b) *200-Gb/s in DWDM 100-GHz grid*: five second-order Gaussian bandpass filters with FWHM bandwidth of 85 GHz.

Modulation Format	OSNR$_{req}$ ($BER_{ref}=10^{-12}$)		Penalty OSNR (Ref: table III)
	100-Gb/s	200-Gb/s	
PDM-NRZ-(D)QPSK	21,9 dB	25,8 dB	+0,9 dB
PDM-67%RZ-(D)QPSK	21,3 dB	25,2 dB	+1,0 dB
PDM-50%RZ-(D)QPSK	21,4 dB	25,3 dB	+1,2 dB
PDM-33%RZ-(D)QPSK	21,0 dB	25,0 dB	+1,3 dB
PDM-CSRZ-(D)QPSK	21,3 dB	25,2 dB	+1,1 dB

Table 4 Tolerance to optical filtering (0.1-nm resolution bandwidth).

Modulation Format	SE$_{WDM}$ *w/o filtering* (b/s/Hz)	SE$_{WDM}$ *with filtering* (b/s/Hz)
PDM-NRZ-(D)QPSK	2	2
PDM-67%RZ-(D)QPSK	1,87	2
PDM-50%RZ-(D)QPSK	1,25	2
PDM-33%RZ-(D)QPSK	1	2
PDM-CSRZ-(D)QPSK	1,54	2

Table 5 Bandwidth and SE of PDM-(D)QPSK in 100 and 200-Gb/s DWDM transmissions.

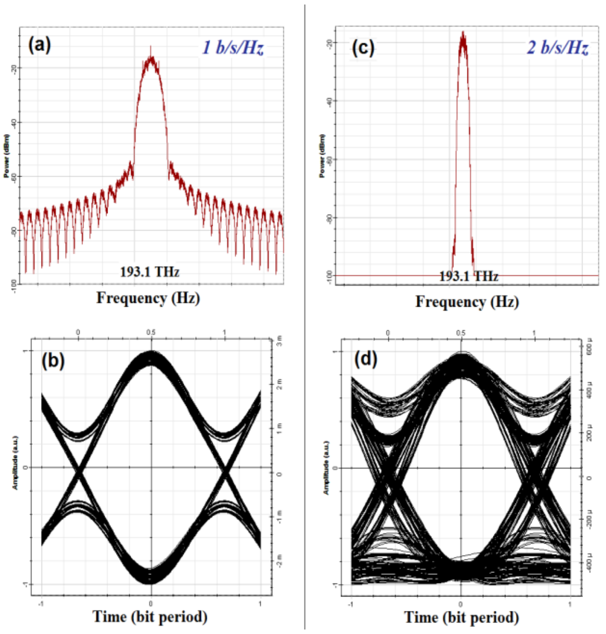

Fig. 3. (a)-(b) Spectrum and eye diagram of PDM-33%RZ-(D)QPSK without filtering. (c)-(d) Spectrum and eye diagram of PDM-33%RZ-(D)QPSK with prefiltering. The distortion in the waveform of this signal by optical filtering is not excessively high, ~1 dB OSNR penalty.

The FWHM value is specified by ITU-T in the Rec. G.694.1 (2012) for DWDM systems [10]. To quantify filtering distortion we have measured the sensitivity of these new schemes for a $BER_{ref} = 10^{-12}$ and then we have compared the results with the sensitivities of Table 3. The values of this analysis are reported in Table 4.

In general, modulation formats with a narrower bandwidth are more tolerant to optical filtering distortion. Minimum distortion is shown in PDM-NRZ-(D)QPSK signal with a 0.9-dB penalty in the OSNR$_{req}$. The higher the pulse temporal width, the smaller the spectral width of the signal, and therefore there will be a lower penalty in the OSNR by optical filtering. Accordingly, the tolerance to filtering distortion of PDM-(D)QPSK is directly proportional to the value of the duty cycle. These affirmations can easily be tested with the results measured: if we increase the duty cycle value in the optical carrier, filtering distortion decreases and the OSNR penalty reaches its minimum value for the NRZ pulses.

Particularly notable is the survey of PDM-33%RZ-(D)QPSK. This signal has half of SE in DWDM systems (1 b/s/Hz), making it impossible to use in filterless optical networks [14]. Nevertheless, the distortion in its waveform by the above filters is not excessively high. This feature will prove to be essential. The handicap of RZ pulses with a low duty cycle is an insufficient SE (< 2 b/s/Hz). However, prefiltering these signals in the TX, the SE can be increased to 2 b/s/Hz (Table 5) with a minimal penalty of ~1 dB in the OSNR (Table 4).

Figure 3 shows the eye diagram of PDM-33%RZ-(D)QPSK. It is just mildly distorted at the output of the filters chain. Filtering distortion results only in a slight amplitude and phase jitter quantified in 1.3-dB OSNR penalty. With 50% RZ and CSRZ PDM-(D)QPSK, the spectral width of the main lobe ranges between 50% and 80% of bit rate, so these modulations can be considered as narrowband signals for the above filters. Hence, the OSNR penalty is so low (≈1 dB).

5 Chromatic dispersion (CD)

Chromatic dispersion is a major impairment in high-capacity optical transmission systems. The spectral components of the optical signal have different group velocities, so that they reach the end of the fiber with different group delays [23,24]. Consequently, chromatic dispersion (also called *Group Velocity Dispersion* – GVD) results in the time domain in dispersive pulse broadening. Dispersion in optical fiber is an all-pass filter on the electric field of the lightwave, given by a complex

Modulation Format	CD_{acum} *w/o filtering* [ps/nm] (2-dB pen.)	CD_{acum} *FWHM = 85 GHz* [ps/nm] (2-dB pen.)
PDM-NRZ-(D)QPSK	**67,8**	91,5
PDM-67%RZ-(D)QPSK	56,4	93,2
PDM-50%RZ-(D)QPSK	54,6	95,0
PDM-33%RZ-(D)QPSK	52,0	**95,1**
PDM-CSRZ-(D)QPSK	49,3	94,0

Table 6 Tolerance to chromatic dispersion for 200 Gb/s transmissions.

transfer function which shows a quadratic dependence in its complex phase with the instantaneous frequency, like a chirp filter. CD produces a variation of the instantaneous frequency in a modulated optical signal [25]. This variation of the instantaneous frequency results in pulse broadening which generates inter-symbol interference (ISI). Obviously, after propagating some distance in the fiber, a point is reached where the accumulating pulse spread is too great for the receiver to recover the signal pulses within the equipment BER specifications.

Table 6 quantifies the accumulated chromatic dispersion (CD_{acum}) required to induce a 2-dB penalty in the OSNR at 200-Gb/s transmissions (100-Gb/s results have been excluded due to space limitations). Obviously, those signals that require more CD_{acum} to reach the 2-dB penalty show better tolerance to this impairment. The second column presents the CD tolerance in filterless optical networks [14], without optical filtering in the simulation scenario (Fig. 2) and the third column assumes the presence of filters. An optical filter disturbs the waveform and the spectrum of the signals, so that the tolerance to CD will also be affected. Currently, optical networks have many devices with filtering in their architectures so this analysis should be performed.

Graphs 4 and 5 also reflect the tolerance differences to CD between PDM-(D)QPSK signals. We can see the OSNR penalty evolution as a function of CD_{acum} for each signal, so that it is relatively simple to check out the formats that are more tolerant to CD with and without optical filtering in the simulation scenario. Attenuation, PMD and fiber nonlinearities have been disabled in the simulation scheme (Fig. 2) to measure the OSNR penalty exclusively due to CD_{acum}. Nonlinearities, like filtering, may also modify the dispersion tolerance: SPM and XPM broaden the bandwidth of the signals and hence their ability to resist the CD. Nevertheless, intrachannel

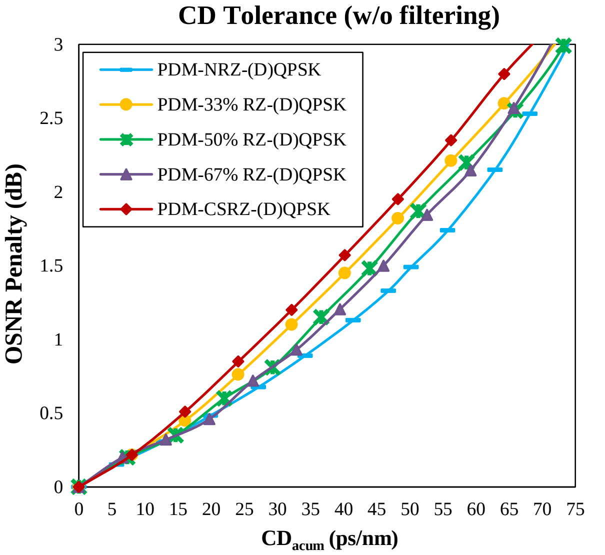

Fig. 4. OSNR penalty as a function of CD_{acum} (ps/nm) without optical filtering.

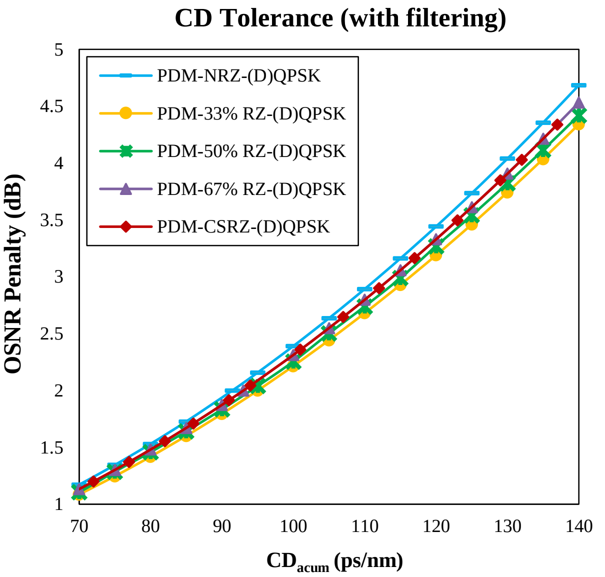

Fig. 5. OSNR penalty as a function of CD_{acum} (ps/nm) with optical filtering.

nonlinearities prevail over interchannel nonlinear effects in WDM systems beyond 40-Gbps/channel, so the results listed in Table 6 are quite similar with and without Kerr effect enabled. SSMF and NZDSF^{+} fibers have been employed to measure the tolerance to CD as objectively as possible (fiber parameters in Table 8). In addition, to include the CD analysis in presence of optical filters in the simulation scenario, five second-order Gaussian bandpass filters were added with the same configuration as in the previous section.

The tolerance of a modulation format to CD with and without filtering is fixed by the spectrum and the waveform launched to the fiber. In a simulation scenario without optical filters these factors are exclusive of the specific modulation employed in the lightpath. In contrast, in the scenario with filtering the waveform and the spectrum are determined by the set *"modulation & filters"*. The narrower the signal spectrum, the higher the tolerance to the CD_{acum}. Filtering process reduces the bandwidth of the signals, so the difference between the group delays of the different spectral components will be smaller.

In the simulation without filtering (the second column of Table 6 and Fig. 4), the signals with more duty cycle have a narrower spectrum, so PDM-NRZ-(D)QPSK and PDM-67%RZ-(D)QPSK are the most tolerant to chromatic dispersion. In contrast, 33% RZ and CSRZ pulses present the worst performance. Particularly, PDM-CSRZ-(D)QPSK, with the optical carrier suppressed, will have better tolerance to fiber nonlinearities but this signal loses robustness against accumulated chromatic dispersion, as same as CSRZ-OOK format [20]. Despite occupying a lower bandwidth than PDM-33%RZ-(D)QPSK, the CSRZ version has the worst tolerance to CD.

On the other hand, the order of the tolerance to CD between the different versions is reversed with optical filtering. As can be seen in the third column of Table 6 and Fig. 5, whereas PDM-NRZ-(D)QPSK shows more resilience to CD than RZ versions in absence of filters, PDM-RZ-(D)QPSK signals are more robust to CD in presence of filters in the network. Filters guarantee identical bandwidths in PDM-(D)QPSK formats, so that CD tolerances are similar (the difference between the group delays of the spectral components hardly vary from one signal to another). Under identical conditions of spectral width, the modulation with the narrowest Gaussian pulses will show more robustness to CD. ISI will be lower than in high duty cycle pulses for the same CD_{acum} value, so that PDM-33%RZ-(D)QPSK will have the most resilience to CD in this case.

Prefiltering PDM-RZ-(D)QPSK formats it is possible to increase their SE to 2 b/s/Hz in DWDM systems and their tolerance to chromatic dispersion. Prefiltering reduces the spectral components, so the difference between the group delays is also reduced. Consequently, the CD tolerance is increased. This feature is essential to understand in Section 7 the great tolerance of this format to intrachannel fiber Kerr nonlinearities, where the chromatic dispersion plays a fundamental role.

Modulation Format	**DGD-100Gb/s** (1-dB pen.)	**DGD-200Gb/s** (1-dB pen.)
PDM-NRZ-(D)QPSK	19,0 ps	7,9 ps
PDM-67% RZ-(D)QPSK	19,4 ps	8,2 ps
PDM-50% RZ-(D)QPSK	19,6 ps	8,4 ps
PDM-33% RZ-(D)QPSK	**20,0 ps**	**8,6 ps**
PDM-CSRZ-(D)QPSK	19,6 ps	8,4 ps

Table 7 First-order PMD tolerance. It shows the DGD (ps) that leads to a 1-dB OSNR penalty.

6 Polarization mode dispersion

In ideal single-mode fibers, the two orthogonal modes that compose the fundamental mode LP_{01} would be degenerated with identical propagation properties because they would have the same cutoff frequency and the same propagation constant.

However, in real single-mode fibers, minute waveguide asymmetries, either due to manufacturing imperfections or due to stress imposed by mechanical vibrations or temperature variations, the circular symmetry between the core and cladding is not perfect [26]. Under these conditions the two orthogonal modes are non-degenerate. They have the same cutoff frequency but their propagation constants are slightly different, exhibiting different group velocities, and giving rise to a *Differential Group Delay* (DGD) [15,27]. Because of the difference between the group delays of both polarizations, the initial pulse is broadened: After square-law detection, the electrical signal is given by the quadratic sum of both polarizations [20]:

$$S(t) = |E_x(t)|^2 + \left|E_y(t - DGD)\right|^2 \qquad (1)$$

This phenomenon is called *Polarization Mode Dispersion* (PMD). If the DGD parameter is constant over wavelength, it is referred to first-order PMD and it predominates over superior PMD orders for many applications. The DGD can be considered constant across a single WDM channel, so the first-order PMD has been studied in a single-channel transmission. The simulation scenario is the same as Fig. 2 with only one TX/RX (193.1 THz channel). A PMD emulator was added between the TX and the RX. Table 7 and Figure 6 have been obtained varying the DGD parameter in the PMD emulator.

Table 7 quantifies the first order PMD tolerance of PDM-(D)QPSK formats in 100 and 200-Gb/s transmissions. It shows the DGD that leads to a 1-dB

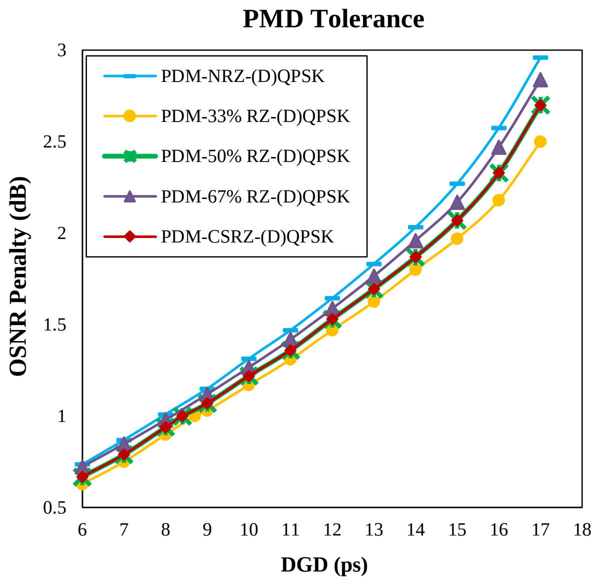

Fig. 6. OSNR penalty as a function of DGD [ps].

OSNR penalty. The first-order PMD tolerance of a modulation format is linear with the symbol period [28]. For most of them, a 1-dB penalty occurs at a DGD value between 30% and 40% of the symbol period. The tolerance of PDM-(D)QPSK formats is very similar and there are no major differences between them, with RZ formats being in general more resilient to PMD than the NRZ version.

The worst result is observed using the NRZ pulses. The Non-Return to Zero pulses, occupying the entire symbol interval, overlap each other with a lower DGD between polarizations. In contrast, PDM-33%RZ-(D)QPSK is the most resilient to PMD (DGD_{MAX}). The reason is simple: the narrower the RZ pulses, the higher DGD required to overlap adjacent pulses with the same ISI-penalty. Therefore, PDM-33%RZ-(D)QPSK requires a higher DGD between polarizations to suffer the same OSNR penalty as pulses with more duty cycle. Meanwhile, PDM-CSRZ-(D)QPSK shows the same tolerance to first-order PMD as a 50% RZ despite having a 67% duty cycle value.

Additionally, Fig. 6 shows the OSNR penalty as a function of DGD for 200G-PDM-(D)QPSK signals (100-Gb/s results are not included due to space limitations, but the order of the tolerances to PMD between 100G-PDM-(D)QPSK formats remains unalterable). It is also obvious that the signal with the lowest duty cycle is the most robust to PMD.

On the other hand, note that the resilience to PMD, in addition, depends to an appreciable extent on the waveforms and filters as well as other residual distortions such as CD and fiber Kerr nonlinearities [19].

7 Fiber Kerr nonlinearities

The effective area of a single-mode fiber typically ranges between 20 and 100 μm² resulting in a strong confinement of the light within the fiber core, so that the optical intensity can easily exceed MW/cm². Due to the presence of an optical intensity so high, the refractive index value could be affected resulting in a phase deviation of the fundamental mode. The refractive index dependence with the optical intensity is known as the Kerr effect [29].

In order to better understand the origin of nonlinearities, the Kerr effect can be classified into more specific nonlinear interactions that can distort optical signals in different ways (Fig. 7). Fiber nonlinearities occurring between pulses of the same WDM channel are referred to as intrachannel nonlinearities and the nonlinearities occurring among two or more WDM channels, the expression interchannel nonlinearities is used [28].

The nonlinear regime of a single-polarization electrical field through a single-mode optical fiber is described by the Generalized Nonlinear Schrödinger Equation (GNLSE) [20,24,29]:

$$\frac{\partial \vec{E}_1(z,t)}{\partial z} + \frac{j}{2}\beta_2(z)\frac{\partial^2 \vec{E}_1(z,t)}{\partial t^2} - \frac{1}{6}\beta_3(z)\frac{\partial^3 \vec{E}_1(z,t)}{\partial t^3} + \frac{\alpha(z)}{2}\vec{E}_1(z,t) = \underbrace{j\gamma\left|\vec{E}_1\right|^2\vec{E}_1}_{SPM-ISPM} + \underbrace{2j\gamma\left\{\left|\vec{E}_2\right|^2 + \left|\vec{E}_3\right|^2\right\}\vec{E}_1}_{XPM-IXPM} + \underbrace{j\gamma\vec{E}_1\vec{E}_2\vec{E}_3^{\,*}}_{FWM-IFWM} \tag{2}$$

In intrachannel nonlinearities $\vec{E}_1$, $\vec{E}_2$ and $\vec{E}_3$ represent the electric fields associated to three different optical pulses from the same WDM channel, meanwhile they represent three different WDM channels in interchannel nonlinearities.

The nonlinear interaction of a channel or a pulse with itself is referred to as self-phase modulation (SPM). Whether SPM relates to an entire channel or an isolated pulse (ISPM) depends on the context [19]. ISPM explains the phase variations in $\vec{E}_1$ which are generated by fluctuations in its own intensity, considering the isolated pulse and without the intervention of adjacent pulses [20]. The intensity variations in $\vec{E}_1$ cause changes

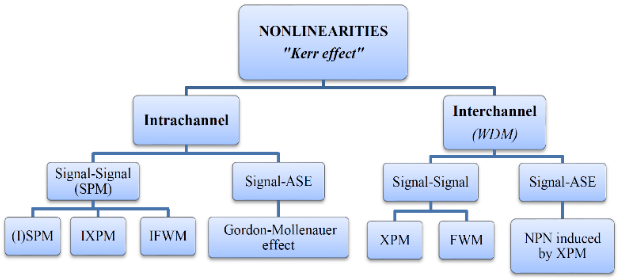

Fig. 7. Classification of Kerr nonlinearities.

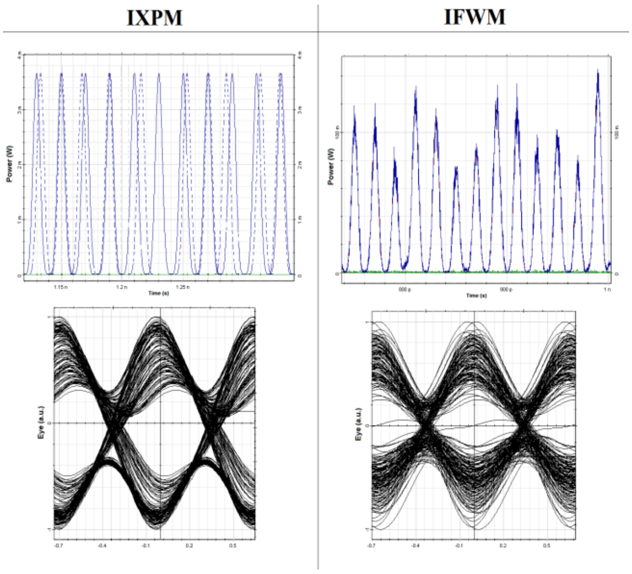

Fig. 8. Effects of IXPM and IFWM on a 100 and 200-Gb/s PDM-(D)QPSK signals. The upper graphs show the signal waveform after transmission. The lower graphs show the eye diagram. The main effect of IXPM is to produce timing jitter, meanwhile IFWM induces amplitude jitter (ghost pulses).

in the refractive index resulting in variations in its own phase.

Intrachannel cross-phase modulation (IXPM) and intrachannel four-wave mixing (IFWM) are the others intrachannel nonlinearities arising from the signal-signal interactions. They are the dominant nonlinear effects beyond 40-Gb/s per channel transmissions. Both phenomena are generated as a result of the overlapping between pulses in a single optical carrier due to CD at the same time that the Kerr effect is being stimulated [19,30]. IXPM explains the pulse phase variations due to intensity fluctuations in the overlapped adjacent pulses. On the other hand, IFWM explains the interaction between three different pulses within the same optical channel. The pulses interaction generates a fourth pulse with random amplitude, often referred as ghost pulse [19,28]. The IXPM effects can be visualized in the eye diagram as phase jitter while IFWM generates amplitude jitter. In Fig. 8 both concepts can be visualized.

The intensity fluctuations generated by ASE noise and adhered over the pulse amplitude are potentially hazardous in presence of SPM. They induce random phase fluctuations (signal-ASE interactions). This phase jitter is a new noise known as nonlinear phase noise (NPN), also referred as the Gordon-Mollenauer effect [17,19,28,31] and it is particularly detrimental for phase-modulated systems between 1 and 20-Gb/s. Beyond 40-Gb/s, the Gordon-Mollenauer effect is not an important nonlinear impairment [21], although optical signals are affected by NPN from intrachannel nonlinearities due to signal-ASE interactions. NPN is especially detrimental in dispersion managed (DM) systems with phase-modulated signals.

Two new phenomena appear associated with signal-signal interactions in interchannel nonlinearities: cross-phase modulation (XPM) and four-wave mixing (FWM) [29]. These nonlinear effects are assumed widely known so they are not described in this paper.

The easiest way to reduce the XPM effects is increasing the spectral separation between optical carriers or using optical fibers with a higher chromatic dispersion coefficient to avoid the spatial overlap between pulses of different WDM channels [15,32]. Beyond 20-Gb/s, XPM is not an important impairment in nonlinear regime [28,29]. Considering the signal-ASE interaction, XPM can induce NPN in adjacent channels. In contrast with the Gordon-Mollenauer effect, NPN induced by XPM cannot be compensated because it is not correlated with the received optical intensity [19], although its impact in the OSNR is lower than the Gordon-Mollenauer effect in SSMF fibers in 10-Gb/s systems [21]. A major consequence of SPM and XPM (signal-signal and signal-ASE interactions) is the spectral broadening of the pulses that increases the channels bandwidth considerably and limits the performance of a lightwave system [25]. Therefore, both phenomena contribute to reduce the system tolerance to chromatic dispersion [28].

On the other hand, FWM is generated, like XPM, due to the nonlinear response of the dielectric polarization with the electric field of the light. Nevertheless, FWM will cease to be a source of degradation in the nonlinear regime beyond 80-Gb/s transmissions [21,32]. According to Winzer's studies [20,21,28,31], intrachannel nonlinearities only prevail beyond 40-Gb/s per channel transmissions: IFWM in SSMF spans and IXPM in NZDSF^{+} spans. Beyond 200-Gb/s, IFWM is the major impairment in the nonlinear regime.

Optical Fiber	SSMF	NZDSF$^+$
D [ps/(nm·km)]	+17	+4
S [ps/(nm^2·km)]	+0.088	+0.084
A_{TH} [dB]	0.2	0.2
A_{eff} [μm^2]	80	72
n_2 **x10^{-20}** [m^2/W]	2.60	3.53
D_{PMD} [ps/km$^{1/2}$]	< 0.1	< 0.1

Table 8 Parameters of SSMF and NZDSF+ fibers [34,35].

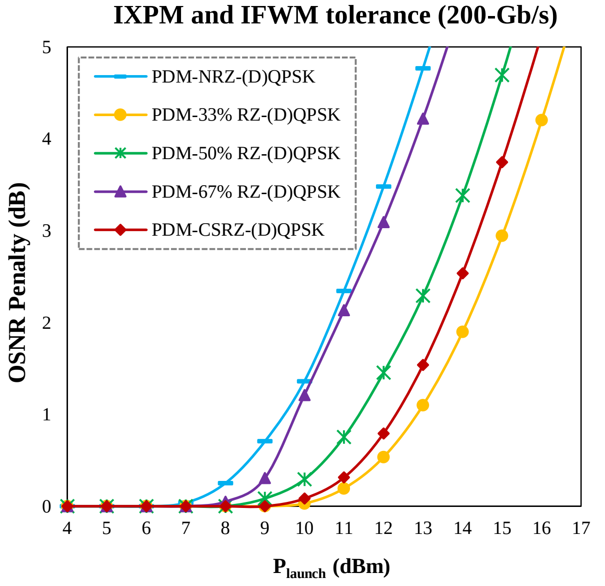

Fig. 9. Tolerance to IXPM and IFWM. OSNR penalty as a function of Plaunch (dBm).

7.1 IXPM and IFWM tolerance

The simulations of this section have been designed to survey the tolerance of 100/200G-PDM-(D)QPSK signals to IXPM and IFWM, the dominant nonlinearities beyond 40-Gb/s. In this section, the simulations have been supported on the DWDM system shown in Fig. 2. The analysis in the nonlinear regime depends on many parameters of the simulation scenario and its operating conditions [33], so one should be very careful with the measurements to obtain conclusions as objective as possible. The presence of IXPM and IFWM is directly related to the GVD coefficient of the fiber, so both phenomena have been analyzed for SSMF and NZDSF$^+$ spans (parameters in Table 8).

Firstly, we initially tested the absence of FWM and XPM in 100 and 200-Gb/s transmissions. DWDM spectrum was controlled along the lightpath, checking that no new spectral components were generated (FWM not found) and the bandwidth of each channel remained unchanged (XPM not found) during the propagation. These tests ensured that the predominant nonlinearities were IXPM and IFWM for both types of fibers.

Afterwards, in Fig. 9, we calculated the OSNR penalty evolution as a function of the power launched into the fiber to find the pulse-shape that is the most robust to IXPM and IFWM in PDM-(D)QPSK signals. We only show the graph for the 200-Gbps-SSMF case because the tolerance order to nonlinear regime among the different pulses does not vary in the other analyzed cases (NZDSF$^+$ and 100-Gb/s). Although the graph for the NZDSF$^+$ has not been included due to space limitations in this document, it is interesting to compare with the SSMF in the nonlinear regime. The robustness to nonlinearities can be increased using the standard single-mode fiber [36] due to a higher CD coefficient, a higher effective area and a lower nonlinear coefficient. Attending to its CD coefficient, optical pulses will be more broadened with a lower distance than in the NZDSF$^+$, so that the peak power of the temporal profile of the pulses will drop before and they will propagate fewer kilometers stimulating the Kerr effect [37]. For the same value of P_{launch} (dBm), the Kerr effect will be stimulated in the SSMF spans during a shorter distance than in NZDSF$^+$ spans.

PDM-(D)QPSK signals exhibit an excellent tolerance to intrachannel nonlinearities. In 100 and 200-Gb/s transmissions, IFWM appears in the SSMF and NZDSF$^+$ whereas IXPM is mainly stimulated in the NZDSF$^+$. In general, phase modulated signals are more robust to IFWM than OOK formats because the relative phase between pulses does not vanish and hence the ghost pulses generated by IFWM have a lower amplitude. 33% RZ and CSRZ pulses are the most tolerant to IFWM and IXPM. Knowing that IFWM and IXPM arise from pulse-to-pulse interactions, the shorter the pulse width, the higher the tolerance to these phenomena [30,38]. With a low duty cycle, RZ pulses need more CD_{acum} to overlap with each other. In that case, there will be a lower peak power in optical pulses with more CD_{acum}, so the Kerr effect will be less stimulated. Therefore, a higher optical power will be necessary to launch into the fiber to achieve the same OSNR penalty as in pulses with a higher duty cycle. Accordingly to Fig. 9, the worst tolerance to IFWM and IXPM is found in the PDM-NRZ-(D)QPSK signal.

However, the high robustness offered by PDM-CSRZ-(D)QPSK is nearly identical to the 33% RZ version. A large resistance to nonlinearities is achieved

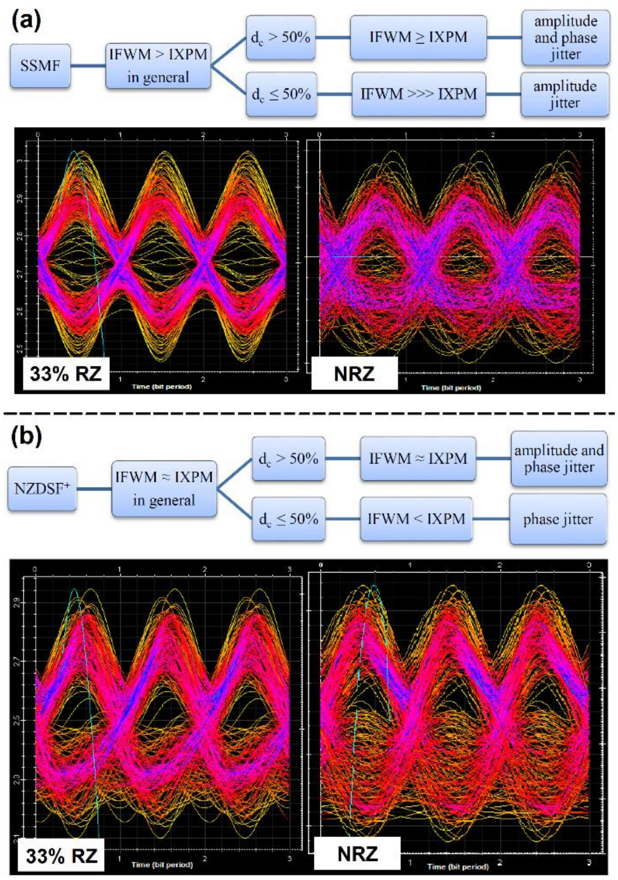

Fig. 10. Eye diagrams of PDM-33%RZ-(D)QPSK (left) and PDM-NRZ-(D)QPSK (right). The distortion induced by IXPM and IFWM results in timing and amplitude jitter, respectively.

suppressing the optical carrier in RZ pulses despite having a higher duty cycle (67%).

7.2 Variation of IXPM and IFWM with the duty cycle

In 100 and 200-Gb/s transmissions, PDM-(D)QPSK signals carry 50 and 100-Gb/s per polarization, respectively (Fig. 1). According to Peter J. Winzer in [28], IFWM predominates in SSMF spans whereas IXPM appears in NZDSF$^+$ spans with bit rates ranging between 50 and 100-Gb/s per polarization. However, the presence of both nonlinearities does not only depend on the optical fiber type, but also the duty cycle value must be taken into account.

A priori, IFWM prevails over IXPM in high dispersion fibers. This is mainly valid with low duty cycles (33% – 50%), but if we set up the optical carrier with a higher duty cycle value (67% – 100%) the stimulation of IXPM will increase, i.e. IXPM is proportional to the duty cycle value. Obviously, the pulse overlapping is more pronounced with a higher duty cycle and consequently the phase is more distorted by the amplitude fluctuations of adjacent pulses. In this situation, the eye diagram is closed by amplitude jitter (associated with the presence of ghost pulses generated by IFWM) and phase jitter (due to NPN generated by IXPM). Therefore, IXPM cannot be ignored in SSMF spans for the PDM-NRZ-(D)QPSK and PDM-67%RZ-(D)QPSK signals (Fig. 10.a).

On the other hand, the differences are not so pronounced in low dispersion fibers for different duty cycle values (Fig. 10.b). In these fibers, PDM-(D)QPSK signals are affected by both intrachannel nonlinearities, without a clear predominance of any of them. For low duty cycles, IFWM is slightly lower than IXPM, so the phase jitter is the main cause of the eye diagram degradation. Meanwhile, IFWM increases with the duty cycle value and puts on the same level as IXPM. In that case, the eye diagram is affected by amplitude and phase jitter.

In general, a high duty cycle value favors the presence of both intrachannel nonlinearities, whereas the GVD coefficient is fundamental to determine the predominant nonlinearity when a low duty cycle is employed: IFWM in SSMF and IXPM in NZDSF$^+$.

8 Conclusions

The amount of traffic carried on optical backbone networks has been growing exponentially over the past two decades. Nowadays, the required capacity on each DWDM channel ranges between 100 and 200-Gb/s. In 2012, the ITU-T recommended the use of *“Flexible-Grids”* networks enabling the possibility to continue working with the PDM-(D)QPSK format beyond 100-G, due to the current technological difficulties to achieve long-haul data communications with the multilevel PDM-16-QAM format, mainly focused on short-reach transmissions.

An intensive analysis has been made of polarization-division multiplexed quadrature phase shift keying modulation formats in 100 and 200-Gb/s DWDM systems. The performance offered by PDM-(D)QPSK varies according to the line code that is employed to carve the pulses of the optical carrier: NRZ, 33% RZ, 50% RZ, 67% RZ or CSRZ. Each option offers different tolerances to linear and nonlinear impairments of a lightpath. The features of PDM-(D)QPSK have been characterized measuring the robustness to ASE noise, crosstalk, optical filtering, chromatic dispersion, polarization mode dispersion and intrachannel nonlinearities.

PDM-33%RZ-(D)QPSK reveals an enormous resistance against the ghost pulses generated by IFWM and the phase fluctuations of IXPM, but the handicap of this signal is its low SE in DWDM systems, 1 b/s/Hz. Thanks to its great tolerance to filtering distortion, the SE may be increased from 1 to 2 b/s/Hz in DWDM systems prefiltering this format in the TX and allowing its integration in the grids of 50 and 100 GHz for 100 and 200 Gb/s transmissions, respectively. In this way, it is possible to exploit the great advantage of RZ pulses with low duty cycle: the reduction of pulse-to-pulse interaction. This feature allows to increase the tolerance to CD, PMD and intrachannel nonlinearities. In contrast, the PDM-NRZ-(D)QPSK format has a slightly higher SE than the other options and it shows better tolerance to filtering distortion and chromatic dispersion in filterless networks.

References

[1] Y. Ayhan, I.H. Cavdar, Optimum link distance determination for a constant signal to noise ratio in M-ary PSK modulated coherent optical OFDM systems, Telecommunication Systems 55 (2014) 461-470.

[2] M. Salsi, J. Renaudier, O. Bertran-Pardo, H. Mardoyan, P. Tran, G. Charlet, S. Bigo, 100 Gb/s and Beyond for Submarine Systems, J. Lightw. Technol. 30 (2012), 3880-3887.

[3] P.J. Winzer, High-Spectral-Efficiency Optical Modulation Formats, J. Lightw. Technol. 30 (2012), 3824-3835.

[4] L. Li, Z. Jijun, D. Degong, Y. Aihan, Analysis modulation formats of DQPSK in WDM-PON system, Optik 123 (2012), 2050-2055.

[5] G. Bennett, Superchannels to the rescue, Lightwave, March/April 2012.

[6] R. Saunders, Coherent DWDM technology for high speed optical communications, Optical Fiber Technology 17 (2011), 445–451.

[7] S. Matthias, Systems with Higher-Order Modulation Impact of Nonlinearities on Fiber Optic Communications", Optical and Fiber Communications Reports 7 (2011), 177-217.

[8] R.H. Walden, Analog-to-digital converters and associated IC technologies, Proc. Compound Semiconductor Integrated Circuits Symposium (2008), 1-2.

[9] J. Yu, Z. Dong, H.-C. Chien, Z. Jia, X. Li, D. Huo, M. Gunkel, P. Wagner, H. Mayer, A. Schippel, Transmission of 200 G PDM-CSRZ-QPSK and PDM-16QAM With a SE of 4 b/s/Hz, J. Lightw. Technol. 31 (2013), 515-522.

[10] ITU-T G.694.1 Recommendation (2012), Spectral grids for WDM applications: DWDM frequency grid.

[11] J. Wang, C. Xie, Z. Pan, Generation of Spectrally Efficient Nyquist-WDM QPSK Signals Using Digital FIR or FDE Filters at Transmitter, J. Lightw. Technol. 30 (2012), 3679-3686.

[12] G. Bosco, P. Poggiolini, M. Visintin, Performance Analysis of MLSE Receivers Based on the Square-Root Metric, J. Lightw. Technol. 26 (2008) 2098-2109.

[13] J. Tellado, M. Louise, C. Hoo, J.M. Cioffi, Maximum-Likelihood Detection of Nonlinearly Distorted Multicarrier Symbols by Iterative Decoding, IEEE Transactions on Communications 51 (2003), 218-228.

[14] C. Tremblay, É. Archambault, M.P. Bélanger, J.-P. Savoie, F. Gagnon, D.V. Plant, Passive filterless core networks based on advanced modulation and electrical compensation technologies, Telecommunication Systems 54 (2013), 167-181.

[15] J.A.M. Pereda, Sistemas y Redes Ópticas de Comunicaciones, Pearson Education, 2004.

[16] A.H. Gnauck, Advanced Amplitude and Phase Coded Formats for 40Gb/s Fiber Transmission, Proceedings of IEEE/LEOS Annual Meeting, page WR1, 2004.

[17] J.P. Gordon, L.F. Mollenauer, Phase noise in photonic communications systems using linear amplifiers, Optics Letters 15 (1990), 1351–1353.

[18] G. Li, Recent Advances in Coherent Optical Communications, Advances in Optics and Photonics 1 (2009), 279-307.

[19] K.-P. Ho, Phase-Modulated Optical Communications Systems, Springer, 2005.

[20] P.J. Winzer, R.J Essiambre, Advanced optical modulation formats, J. Lightw. Technol. 24 (2006), 4711-4727.

[21] P.J. Winzer, A.H. Gnauck, Optical Phase-Shift-Keyed Transmision, J. Lightw. Technol. 23(2005), 115–130.

[22] Y. Aihan, L. Li, Z. Xinliang, Analysis of modulation format in the 40Gbit/s optical communication system, Optik 121, (2010) 1550–1557.

[23] G.P. Agrawal, Fiber-Optic Communication Systems, Wiley Interscience, Four Edition, 2010.

[24] J.M. Senior, Optical Fiber Communications, Principles and Practice, Prentice Hall. 2009.

[25] B.A.E. Saleh, M.C. Teich, Fundamentals of Photonics, John Wiley & Sons, 1991.

[26] J.P. Gordon, PMD fundamentals: Polarization mode dispersion in optical fibers, PNAS 97 (2000), 4541-4550.

[27] J.P. Elbers, Modelling of polarization mode dispersion in single mode fibers, Electronics Letters 33 (1997), 1894-1895.

[28] P.J. Winzer, R.J Essiambre, Advanced optical modulation formats, Optical Fiber Telecommunications V B: Systems and Networks, Elsevier, 2008.

[29] G.P. Agrawal, Nonlinear Fiber Optics, San Diego: Elsevier Science & Technology, 5th edition, 2013.

[30] L. Lujiao, Q. Yaojun, J. Yuefeng, Suppression of intra-channel four-wave mixing in 40 Gbit/s RZ-DQPSK transmission with alternate-polarization, Optik 122 (2011), 2242– 2245.

[31] H. Kim, P.J. Winzer, Nonlinear Phase Noise in Phase-Coded Transmission, in Proc. OFC, page OThO3, 2005.

[32] D.P. Abellán, F.P. Ramos, J.C. Francoy, Sistemas de Comunicaciones Ópticas, Universidad Politécnica de Valencia, 2006.

[33] R. Hui, M. O'Sullivan, Fiber Optic Measurement Techniques, Elsevier Academic Express, 2009.

[34] Corning Incorporated, Datasheet Corning® LEAF® Optical Fiber, 2011.

[35] Corning Incorporated, Datasheet Corning® SMF-28e+® Optical Fiber, 2011.

[36] M.S. Alfiad, D. Van den Borne, T. Wuth, M. Kuschnerov, H. Waardt, On the Tolerance of 111-Gb/s POLMUX-RZ-

DQPSK to Nonlinear Transmission Effects", J. Lightw. Technol. 29 (2011) 162-170.
[37] M.Y. Hamza, N. Akhtar, N. Sarwar, S. Yang, Evolution behavior of chirped tan-hyperbolic pulse through single mode fiber in the simultaneous presence of fiber loss, dispersion and self-phase modulation, Telecommunication Systems 55 (2014), 451-459.
[38] K.S. Cheng, J. Conradi, Reduction of pulse-to-pulse interaction using alternative RZ formats in 40-Gb/s systems, IEEE Photon. Technol. Lett. 14 (2002), 98–100.